Switchable single-longitudinal-mode dual-wavelength erbium-doped fiber laser based on one polarization-maintaining fiber Bragg grating in linear cavity

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Abstract. Switchable single-longitudinal-mode (SLM) dual-wavelength erbium-doped fiber laser at room temperature is demonstrated. One fiber Bragg grating (FBG) directly written in a polarization-maintaining and photosensitive erbium-doped fiber as the wavelength-selective component is used in a linear laser cavity. Because of the polarization hole burning enhanced by the polarization-maintaining FBG, the laser can be designed to operate in stable dual-wavelength or wavelength-switching modes with a wavelength spacing of 0.202 nm by adjusting a polarization controller. The stable SLM operation is guaranteed by a saturable absorber. The optical signal-to-noise ratio of the laser is >40 dB. The amplitude variation in nearly 1.5 h is <0.5 dB for both wavelengths.
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Subject terms: optical erbium-doped fiber lasers; single-longitudinal-mode; polarization-maintaining fiber Bragg grating; polarization hole burning.

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1 Introduction

Multiwavelength fiber lasers have attracted much interest because of their potential applications in wavelength-division-multiplexed (WDM) fiber communication systems, optical fiber sensing, instrument testing, microwave photonic systems, and so on, due to their various advantages, such as multiwavelength operation, low cost, and compatibility with fiber optic systems. It is difficult to obtain simultaneous multiwavelength lasing at room temperature in erbium-doped fiber (EDF) lasers because EDF is the primary homogeneous gain medium. Various multiwavelength fiber lasers based on fiber Bragg gratings (FBGs) have been demonstrated because FBGs have advantages such as wavelength-selective nature, fiber compatibility, ease of use and fabrication, and low cost.[1–5] Multiwavelength fiber lasers using the polarization-maintaining FBGs (PMFBGs) have recently attracted considerable research attention.[4,5] However, these multiwavelength fiber lasers are not single-longitudinal mode (SLM) owing to the long lasing cavity, which limits their practical applications due to multimode oscillation and mode hopping. Chen et al.[6] proposed dual-wavelength SLM laser utilizing an ultranarrow dual-transmission-peak bandpass filter in a ring cavity. They also demonstrated the dual-wavelength SLM laser in a linear laser cavity.[7] Nevertheless, the required bandpass filters must be specially designed with the equivalent phase-shift technique and the spacing between the two transmission wavelengths is restricted by the reflection bandwidth. Li et al.[8] proposed dual-wavelength emission from cascaded distributed feedback fiber lasers, but the FBGs need to be specially fabricated for the lack of photosensitivity of the phosphate glass fiber. The dual-wavelength SLM fiber laser presented by Guan et al.[9] also has this problem. Another way to achieve the dual-wavelength lasing is writing the superimposed chirp FBGs (SCFBGs) in the photosensitive erbium-ytterbium co-doped fiber,[10] but this kind of fiber is very expensive. Both the SCFBGs and the Fabry–Pérot etalon filters can also be used to obtain the SLM dual-wavelength fiber lasers,[11–13] but the lasing wavelength spacing cannot be large owing to the mode-selective principle. Although the problem can be solved by using individual uniform apodized FBGs,[14] it is need to align the central transmission peak of the SCFBGs or the FP etalon filters with the individual FBGs precisely. Sun et al.[15] presented SLM dual-wavelength fiber ring laser using Sagnac filters and a saturable absorber (SA) with a complicated configuration and operating principle. However, the gain competition was not well suppressed and the lasing wavelength spacing was over 8 nm, which limited its application. Qian et al.[16] demonstrated a SLM dual-wavelength fiber ring laser using the Mach–Zehnder comb filter incorporating with the counterpropagation of the two light beams. Chen et al.[17] also proposed SLM dual-wavelength fiber ring laser using the Mach–Zehnder comb filter and a SA. However, we all know that the Mach–Zehnder comb filter is more sensitive to temperature and the environment vibration compared to the FBGs. Pan et al.[18] presented a switchable SLM dual-wavelength fiber ring laser by using a passive triple-ring cavity and a hybrid gain medium. But the parameters of the laser need to be properly adjusted to guarantee the operation. Recently, Pan et al.[19] also proposed a wavelength-switchable SLM dual-wavelength erbium-doped fiber laser for switchable micro-

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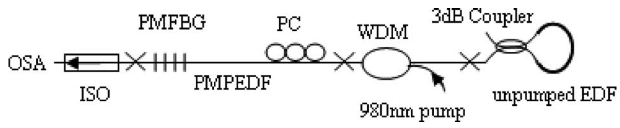

Fig. 1 Schematic diagram of the proposed laser.

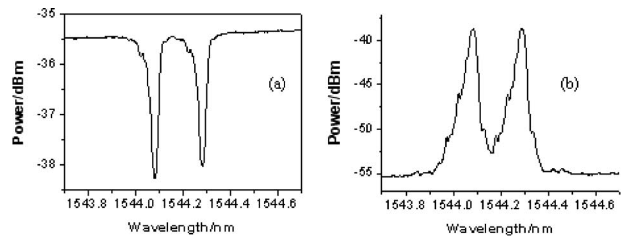

Fig. 2 The transmission spectra (a) and reflection spectra (b) of PMFBG.

wave generation using the same technique which was presented by Qian et al.[16] Dual-wavelength SLM Brillouin fiber laser has also been proposed to achieve photonic generation of microwave millimeter-wave sources.[20]

In this paper, we demonstrate a simple room-temperature switchable SLM dual-wavelength EDF laser based on one PMFBG, incorporating a SA in a linear laser cavity. Because of the polarization hole burning (PHB) enhanced by the PMFBG, the laser can be designed to operate in stable dual-wavelength or wavelength-switching modes with a wavelength spacing of 0.202 nm by adjusting a polarization controller (PC). The stable SLM operation is guaranteed by a SA. The optical signal-to-noise ratio (OSNR) is >40 dB. The amplitude variation in nearly 1.5 h is <0.5 dB for both wavelengths. The proposed scheme offers a possibility for photonic generation of a microwave signal.

2 System Configuration and Principle

The schematic diagram of the proposed laser is shown in Fig. 1. The linear cavity laser consists of a uniform PMFBG directly written in the tail of polarization-maintaining and photosensitive erbium-doped fiber (PMPEDF) as the wavelength-selective component of the laser, a Sagnac loop mirror constructed with a 3-dB coupler as perfect broadband reflection mirror with nearly 100% reflectivity for 1550-nm spectral region, a 980/1550-nm WDM a section of unpumped EDF, a PC, and an optical isolator. The PMPEDF of about ~1 m long with an absorption coefficient of 22.5 dB/m at 1530 nm is twisted on a PC and pumped by a laser diode with a maximum output of ~120 mW at 980 nm through the WDM. A 5-m unpumped EDF, with an absorption coefficient of 16 dB/m at 1530 nm, is inserted into the Sagnac loop as a SA, acting as a narrow multiband filter. It has been shown that a section of unpumped EDF in a Sagnac loop can be used as a saturable absorber in which two counterpropagating waves form a standing wave. The refraction index of the unpumped EDF changes spatially due to the standing wave, and this results in an ultranarrow bandwidth self-induced FBG acting as a tracking filter and eliminating mode hopping.[21,22] Thus, the SA can ensure the stable laser operation in a SLM. The PC is used to rotate the polarization state, which allows continuous adjustment of the birefringence within the cavity to balance the gain and loss of different wavelength and restrain the spatial hole-burning effects in a liner cavity produced by the two counterpropagating waves in laser gain material to some extent. The total length of the laser cavity without the SA connected is ~2 m, which means that the adjacent mode spacing is ~50 MHz. When the 5-m unpumped EDF was connected, the length of the laser cavity become 7 m, then the adjacent mode spacing is ~14 MHz.

The PMFBG with a grating section of ~4 cm was fabricated using a uniform phase mask (with a phase mask period of 1068 nm) and KrF excimer laser. Because of different modal refractive index along the fast and slow axes, the PMFBG exhibits two reflection peaks, one for each polarization. The PMPEDF has a beat length of 7.88 mm at 1550 nm, which corresponds to a wavelength separation of ~0.202 nm of two reflection peaks. In theory, the maximum transmission strength of the PMFBG for the corresponding polarizations with an unpolarized amplified spontaneous emission (ASE) source is 3 dB, respectively. Thus, here we define that the strength of 3 dB corresponds to the reflection of 100% for the corresponding polarizations, respectively. The two reflection peak wavelengths of the PMFBG were 1544.084 nm with a 3 dB bandwidth of 0.036 nm and 93% reflectivity and 1544.287 nm with a 3 dB bandwidth of 0.036 nm and 88% reflectivity. The transmission and reflection spectra of PMFBG with an unpolarized ASE source are shown in Fig. 2. The spectral characteristics were measured by using an ANDO AQ6317 optical spectrum analyzer (OSA) with 0.01-nm resolution.

Feedback from the PMFBG in the laser cavity results in different linearly polarized modes, which are separated both in wavelength and polarization. The polarized angles, varied with the PC states, have the relationship with the lasing wavelengths. Lasers operating on different linearly polarized modes greatly enhance the PHB in the cavity and reduce homogeneous linewidth of the EDF.[4,5] Here, for example, we suppose that the transverse magnetic (TM) polarization has a dominant position in lasing, and then the transverse electric (TE) polarization will achieve the higher gain than the TM polarization, which will weaken the mode competition and make them reach equilibrium state gradually in lasing, and vice versa. Furthermore, the PC can adjust the gain and loss of different wavelength in the laser cavity. Thus, due to the PHB enhanced by the PMFBG, by adjusting the PC states, TE, TM polarization, or both of them can be individually excited for the incident light with different polarized angles. Namely, the laser can be designed to operate in stable dual-wavelength or wavelength-switching modes by adjustment of the PC at room temperature.

3 Experimental Results and Discussion

When 30 mW of pump power was coupled into the laser, the dual-wavelength operation of the laser began to come out stably. First, we investigated the stable dual-wavelength operation or wavelength-switching modes without the SA connected in the laser cavity. Figure 3 shows the dual-wavelength operation of the laser with lasing wavelengths 1544.105 and 1544.307 nm, respectively, corresponding to

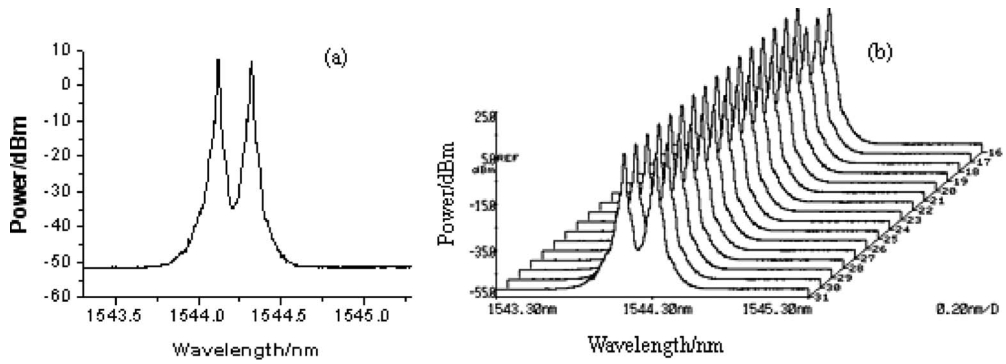

Fig. 3 Dual-wavelength operation of the laser at ~110 mW pumped.

the two reflection peak wavelengths of the PMFBG with ~110 mW pumped power. The OSNR, as shown in Fig. 3(a), was measured to be >40 dB. The peak power of the fiber laser is ~7.5 dBm. The 3-dB bandwidth measured by using an OSA with a wavelength resolution of 0.01 nm is 0.013 nm. Sixteen times repeated scans at 5-min intervals in nearly 1.5 are shown in Fig. 3(b). The amplitude variation of the two lasing wavelengths was <0.5 dB. Figure 4 shows the single-wavelength operation of the proposed laser with pumped power of ~110 mW. Figures 4(a) and 4(c) indicate the lasing spectra of 1544.105- and 1544.307-nm wavelength operation with peak power of about 9.6 and 9.4 dBm, respectively. The 3-dB bandwidth is 0.013 nm. sixteen times repeated scans at 5-min intervals in nearly 1.5 h are shown in Figs. 4(b) and 4(d). The amplitude variation was measured to be <0.5 dB in each single operation, and the OSNR was for both >60 dB. In the experiment, the dual- and single-wavelength operations were very stable to pump variations and no significant drift in wavelength or amplitude variation was discovered under an invariant pump. Note that higher output power, efficiency, and OSNR can be achieved by optimizing the reflectivity of the PMFBG and the length of PMPEDF.

One thing that should be pointed out is that the lasing wavelengths began to drift (but not significantly) to the longer wavelength with the pumped power rising. Take the lasing wavelength 1544.092 nm as an example, when the pumped power rise from 30 to 110 mW, the lasing wavelength drifted from 1544.092 to 1544.105 nm. But once the pumped power was fixed, the lasing wavelength was fixed. We think it is caused by the pump-induced thermal effects

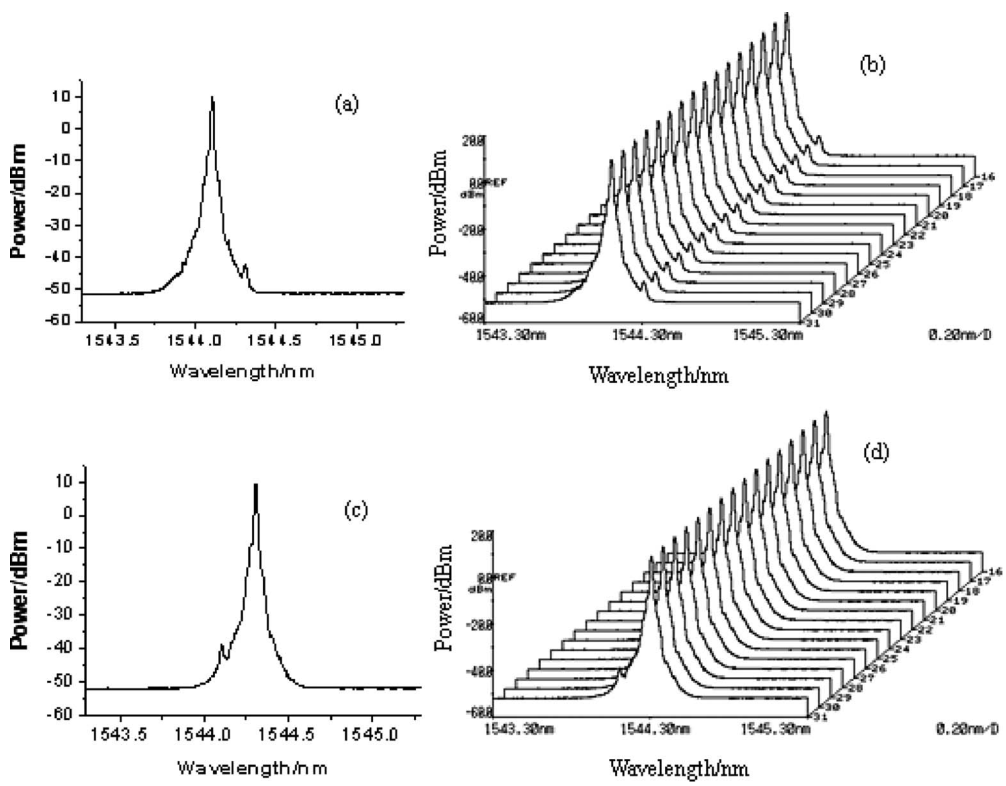

Fig. 4 Single-wavelength operation of the laser at ~110 mW pumped.

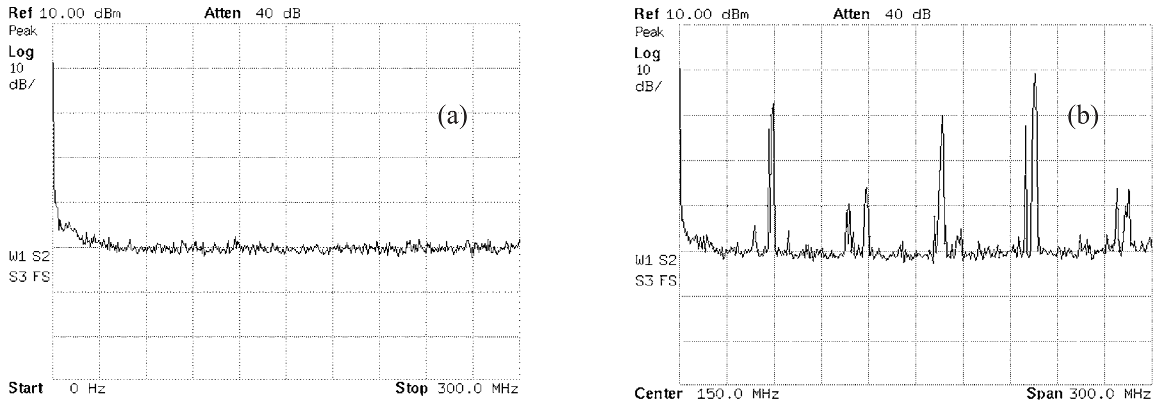

Fig. 5 Electrical spectrum of the beating signals.

of the PMFBG.[23] And the problem can be solved by packaging the PMFBG or using the temperature controlled circuit.

Then, we inserted the SA into the laser cavity. The peak power of the fiber laser of dual- and single-wavelength operations with ~110 mW pumped power was 5.0, 7.1, and 7.2 dBm, respectively. Namely, the efficiency of the fiber laser becomes worse when the SA was inserted into the laser cavity. The SLM operation was verified through the delayed self-homodyne method. We applied the laser output to a Mach–Zehnder fiber interferometer with an 8-km delay line connected to a 10-GHz photodetector, and then monitored the electrical beating signal through an electrical spectrum analyzer (ATTEN 6030D, 9 kHz–3 GHz). Figure 5(b) shows the electrical beating signals when the SA was disconnected. Evidently, the fiber laser operated in multimode oscillation with a strong beating noise caused by mode beating. Figure 5(a) shows the electrical beating signals when the SA was inserted into the Sagnac loop; no beating noise appears, which indicated that the fiber laser is at the SLM operation. The linewidth of the laser should be measured using the delayed self-heterodyne method. However, according to the current laboratory conditions, we do not have an acousto-optical modulator.

Such a fiber laser has potential application in the fiber-optic sensing system. Furthermore, a dual-wavelength SLM fiber laser has potential applications in microwave or millimeter-wave signal generation and modulation of data on the microwave subcarrier.[11–13] According to the laboratory conditions, we do not have an electrical spectrum analyzer with a large span to observe the millimeter-wave signal generation and the detailed parameters. A change in the temperature of the laser will shift the two wavelengths, simultaneously, but will not affect the wavelength spacing and stability. Different lasing wavelengths can be obtained by tuning the strain of the PMFBG or changing the period of the custom gratings. And different wavelength spacing can be achieved by controlling the birefringence of the PMFBG,[9] choosing different PMPF or using the cascaded PMFBGs.[4] Thus, dual-wavelength SLM fiber lasers with different wavelength spacing for photonic generation of a microwave signal can be obtained.

4 Conclusion

We demonstrated a room-temperature switchable dual-wavelength EDF laser based on one PMFBG, incorporating a SA in a linear laser cavity. Because of the PHB enhanced by the PMFBG, the laser can be designed to operate in stable dual-wavelength or wavelength-switching modes with a wavelength spacing of 0.202 nm at room temperature by adjusting a PC. The stable SLM operation is guaranteed by a SA. The OSNR is over 40 dB. The amplitude variation within 16 times scans in nearly 1.5 h is less than <0.5 dB for both wavelengths. We provide a simple way to obtain the SLM dual-wavelength fiber laser, and its potential application is also discussed.

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